Multiscale Deterministic Wave Modeling with Wind Input and Wave Breaking Dissipation

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LONG-TERM GOAL

The primary focus of this research is to use large-eddy simulation (LES) and large-wave simulation (LWS) to obtain improved physical understanding of wind-wave-ocean interactions, based on which we aim to develop effective models of wind input and whitecapping dissipation for phase-resolving, nonlinear wave-field simulation at large scales. Our ultimate goal is to establish a numerical capability for predicting deterministically large-scale nonlinear wave-field in real marine environments with the presence of significant wind and wave breaking effects.

OBJECTIVES

The scientific and technical objectives of this research are to:

- develop advanced LES and LWS numerical capabilities for wind-wave-ocean interactions with physics-based subgrid-scale (SGS) models; use high-performance LES/LWS as a powerful research tool to obtain an improved understanding of the flow structure in the atmosphere-ocean wave boundary layer

- develop effective models for wind input and the associated whitecapping dissipation in a direct phase-resolving context, which can be readily incorporated into the deterministic numerical tool of the Simulation of Nonlinear Ocean Wave-field (SNOW)

- understand effects of multi-scale physics and environmental uncertainties upon wave deterministic propagation, and to effectively model these effects; validate the direct modeling and simulation approach, and perform direct comparison with existing theories and field measurements

APPROACH

We use a systematic, multiscale approach to investigate and to model effects of wind input and whitecapping dissipation on wave-field evolution. This includes: (1) use LES and LWS to obtain improved physical understanding of wind-wave-ocean interactions at small scales (O(1~10) significant gravity wave lengths); (2) based on the LES/LWS results, develop advanced wind input and whitecapping models in a direct physical context in terms of surface pressure distribution and flow field filtering, respectively; and (3) incorporate the models into SNOW simulation to investigate local

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effects of wind forcing and whitecapping on large-scale wave-field evolution. Because the physics are being investigated and modeled in a direct, phase-resolving context, we expect models developed in this study are more likely to succeed than traditional phase-averaged parameterizations.

The numerical study of wind-ocean-wave interactions are at two fronts: viscous flow simulation for turbulence-wave interactions at small scales, and potential flow based wave simulation at large scales. For viscous air-wave-water simulations, we use the approach of large-eddy simulation based on filtered Navier-Stokes equations, in which large turbulence eddies are computed explicitly with effects of small eddies being represented by SGS models. A similar LWS approach is used for wave-turbulence interactions, with large wave components being simulated directly and small wave effects modeled.

One of the major issues with simulating coupled air-wave-water turbulent flows is the presence of a deformable, time-evolving free surface, which makes the air and water computational domains irregular. The location and geometry of the free surface are unknown beforehand, and they are part of the solution to be solved for. To overcome this difficulty, we have developed a suite of complementary computational methods, which include a boundary interface tracking method based on boundary-fitted grids for moderate wave slope and an Eulerian interface capturing method based on a level set approach for steep/breaking waves.

The wind input and whitecapping models developed from LES/LWS study will be incorporated to potential flow wave computation using SNOW developed at MIT. The SNOW uses a high-order spectral (HOS) method, which is a pseudo-spectral method developed based on the Zakharov equation and mode-coupling idea. The wind input to the wave-field is modeled by surface distribution of pressure, while wave breaking dissipation is represented by advanced filtering treatment in physical and spectral spaces.

The multiscale modeling of ocean wave-fields will be one of the foci of this research. At local scales, we apply LES and LWS, with which the large eddies and waves are resolved explicitly and structures smaller than the computational grid are modeled. The wind input and models developed based on local-scale LES/LWS are then implemented in SNOW for large-scale simulations. In SNOW, the nonlinear wave interactions, the wind input, and the whitecapping dissipation are all represented in a direct physical context. This approach provides a powerful tool and a unique opportunity to investigate the effects of local processes on large-scale wave-field evolution in a physical-based, deterministic way.

Large-scale high-performance computation on parallel computers is used to meet the computational challenges in the turbulence and wave simulations. Massage passing interface (MPI) based on domain decomposition is used for parallelization.

WORK COMPLETED

During the fiscal year of 2006, substantial progresses have been made in the areas of:

- Establishment of extensive simulation datasets of wind-wave interaction for various wave steepness and wave ages.
- Investigation of effect of wave nonlinearity and wind drift on flow dynamics.

- Investigation of coherent flow structures in turbulence-wave interactions. We also quantified turbulence kinetic energy (TKE) budget and enstrophy balance.
- Theoretical study of wave evolution under the action of winds.
- Quantification of wind input to waves based on pressure data obtained from simulations. Effect of wave slope, wave age, wind drift, and wave nonlinearity on pressure variation has been elucidated.
- Investigation of wave breaking modeling and simulation.

RESULTS

In order to model wind input to ocean wavefield, we have performed an extensive study on the interaction of turbulence winds with surface waves at a wide range of wave age and wave steepness parameters. Effects of wave nonlinearity and wind drift have also been investigated. From our simulation, we are able to obtain a full description of the instantaneous, three-dimensional flow field. Figure 1 shows an example of vortex structures in the wind turbulence near surface waves. It is shown that semi-streamwise vortices are the dominant vortex structures near the wavy surface and the evolution of vortices is constantly interrupted by the wave crests and troughs.

With the extensive simulation data obtained, we are able to quantify terms in the turbulent kinetic energy (TKE) budget, which are plotted in Figure 2. In this report, only results for wave slope of $ka = 0.25$ are shown due to space limitation. For the young wave (wave age $c/u^* = 2$), large production emanates at the crest and then lifts above the trough. The transport has its minimum above the trough, while its maximum occurs in front of the crest. As the wave age increases (wave ages $c/u^* = 14$ and 25), the region of maximum production moves to the front of the crest, while the region of maximum transport moves to the leeside of the crest with the region of minimum transport almost unchanged. Peak dissipation coincides with peak production in all cases. Viscous diffusion is negligible compared to other terms, with the exception of the region very close to the surface. The above results establish a physical basis for the development of turbulence modeling and flow parameterization.

To understand the effect of wave age on vortex structures, we calculated the phase averaged turbulent enstrophy and the terms in enstrophy budget. Figure 3 shows phase averaged turbulent enstrophy components in streamwise, transverse, and vertical directions, respectively. The high intensity regions for streamwise and vertical components correspond to semi-streamwise vortices shown in Figure 1. The distribution of transverse enstrophy is mainly caused by the vertical profile of phase averaged streamwise velocity. Figure 3 also shows the dominant production terms in turbulent enstrophy budget. It is found that the peak of stretching production is located in front of the crest for the young wave with $c/u^* = 2$, while for intermediate ($c/u^* = 14$) and mature waves ($c/u^* = 25$), it is located above the crest. This feature of stretching production distribution coincides with the distribution of streamwise enstrophy itself. The mixed production has similar distribution compared to stretching production, but with reversed sign.

The Gortler instability, which states that a boundary layer flow over a concave geometry generates semi-streamwise vortices, seems to be important for the incidence of semi-streamwise vortices. To illustrate this mechanism, phase-averaged streamlines of Eulerian velocity for various wave ages are shown in Figure 4. It is shown clearly that the peak of streamwise component of turbulent enstrophy (Figure 3) coincides with the concave streamlines. The wave age parameter influences the semi-streamwise vortices by changing the position and the curvature of the concave streamlines.

Previous studies in the literature often overlooked effects of wave nonlinearity and wind-induced surface drift, which we found to be significant for some cases. Figure 5 shows an example of the influence of wind-induced surface drift on turbulent statistic quantities. It is found that for the TKE budget, the existence of a surface drift results in a phase shift towards downstream, and this effect is significant for young waves while less obvious for mature waves. The transverse component of turbulent enstrophy for young waves is also affected by the wind-induced surface drift, as shown in Figure 5.

An ultimate goal of this project is to obtain wind input parameterization for phase-resolved, deterministic wavefield prediction using HOS. Figure 6 shows phase-averaged pressure distribution along the water wave surface. For the young wave ($c/u_* =$ 2), the positive pressure in front of the crest and the negative pressure behind the crest result in an energy input to the wavefield. For intermediate ($c/u_* =$ 14) and mature ($c/u_* =$ 25) waves, the surface pressure is almost symmetric about the wave crest, which results in reduced input to the wave field. For the young wave, with the presence of a wind-generated surface drift, the two peak locations of the surface pressure shift downstream, resulting in an even larger form drag and energy input. For intermediate and mature waves, the influence of surface drift on surface pressure distribution is negligible.

The pressure quantification obtained in Figure 6 will play an important role in wind input modeling for HOS-based wave simulation. In the fiscal year of 2007, we have developed a theoretical approach for the investigation of wind effect on the phases of propagating waves. Numerical implementation, validation, and test of wind input modeling in HOS simulation are currently underway.

For wave breaking dissipation, we developed an approach for LES/LWS of multiphase flows in the fiscal year of 2007. We use an accurate and effective Eulerian approach for the simulation of air and water mixed flows, in which different phases of fluids are treated as a coherent system with varying physical properties. We also extended LES to LWS of multiphase flows. The coexistence of air and water and the presence of an interface among the two phases introduce new SGS effects to be modeled. Large wave simulation is used to capture the grid-scale interface topology, with the small-scale interface wiggles/roughness and bubble/droplet effects being modeled by SGS terms.

IMPACT/APPLICATION

This project aims at basic scientific understanding of the air-sea-wave interaction physics and numerical capability development for ocean wave-field prediction pertinent to Navy applications. It addresses a critical need of the Navy to bridge the gap between the modeling of small-scale air-sea-wave interaction physics and the prediction of ocean waves at regional scales. The proposed research will provide the Navy with a new powerful tool to predict deterministically nonlinear, large wavefield with finely-resolved temporal and spatial detail. The new phase-resolved, deterministic tool is fundamentally distinct from existing phase-averaged, statistical wave modeling tools such as WAM and SWAN, with the potential of being able to make more accurate prediction because of its direct, physics-based approach. Furthermore, the results of this work will also be useful for the comparison and calibration of field measurements and for obtaining physical insights to improve existing phase-averaged wave prediction models.

RELATED PROJECTS

This work compliments a number of on-going ONR projects. In particular, it is closely related to the development of Simulation of Nonlinear Ocean Wave-field (SNOW) by Professor Dick Yue's research group at MIT. The wind input and wave breaking dissipation modeling in this project is to be incorporated into SNOW, and together we will improve the SNOW capability for it to become a next generation of wave model capable of predicting nonlinear wave evolution subject to winds and whitecapping. Such numerical tools will be useful for high-resolution wave-field study.

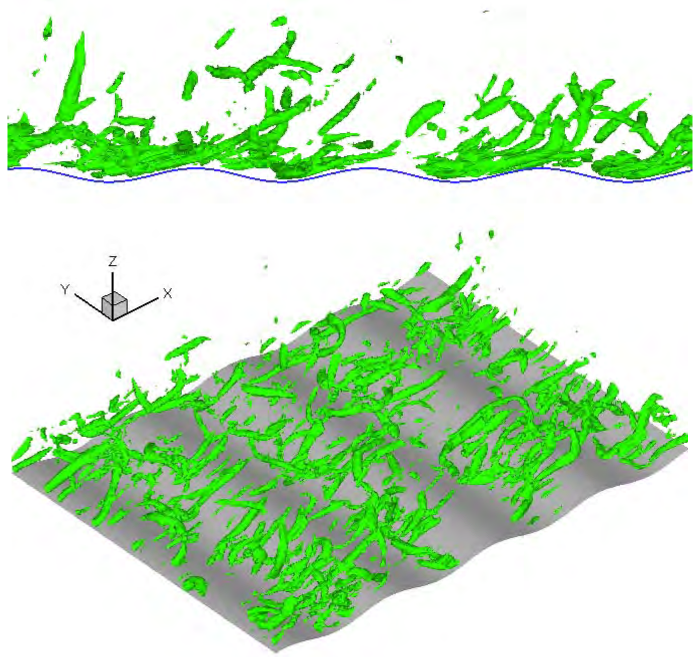

Figure 1. 2D and 3D views of vortex structures in wind over waves. The wind is blowing in the $x-$ direction. Here the vortices are represented by isosurfaces of second largest eigenvalue of the tensor $\mathbf{S}^2+\mathbf{\Omega}^2$, with $\mathbf{S}$ and $\mathbf{\Omega}$ respectively the symmetric and anti-symmetric parts of the velocity gradient tensor $\nabla\vec{u}$.

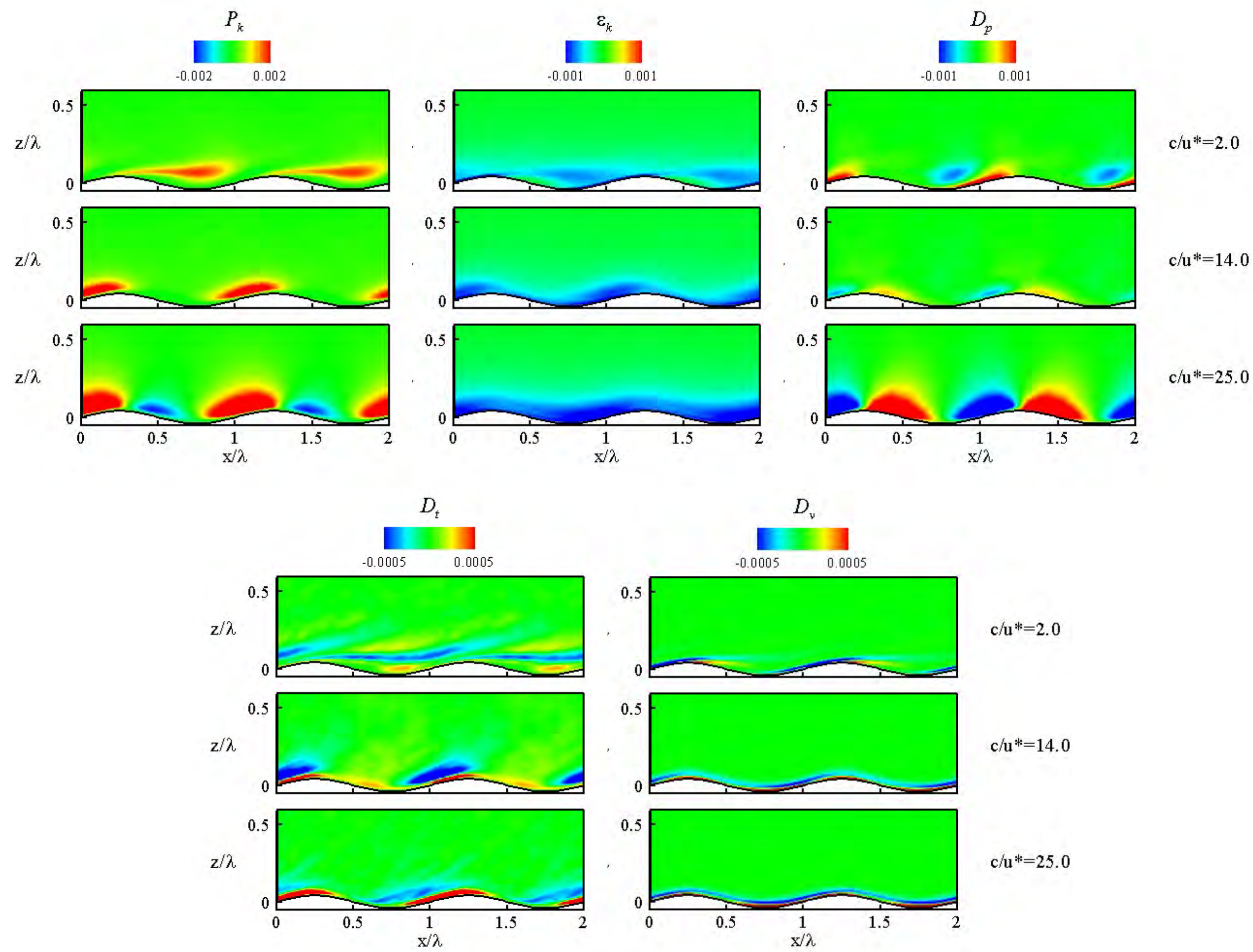

Figure 2. Terms in turbulent kinetic energy budget for surface waves with various wave ages. Here P_k is production; D_v is viscous diffusion; D_p is pressure transport; D_t is turbulent transport; and ε_k is dissipation.

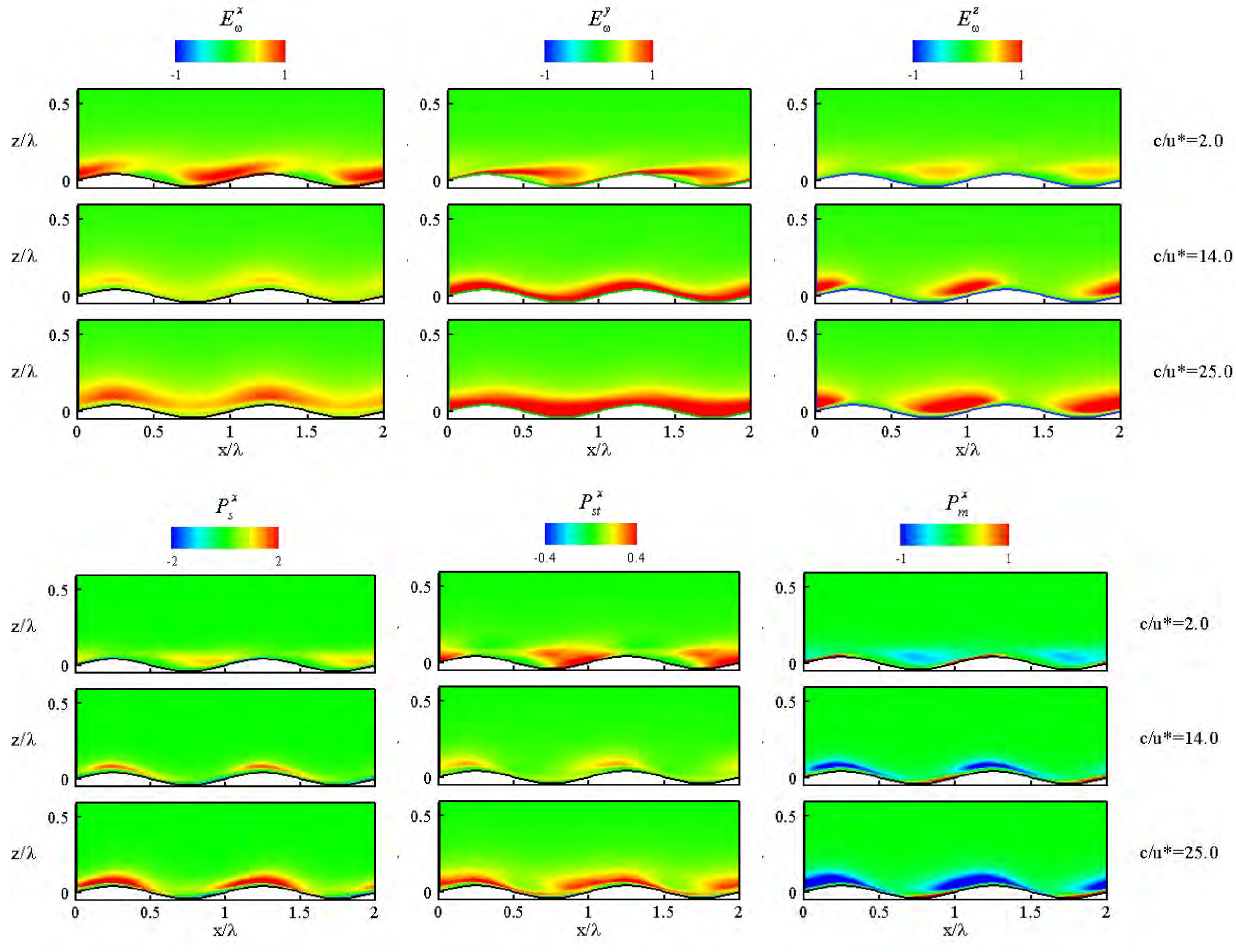

Figure 3. Turbulent enstrophy and dominant production terms in enstrophy budget for surface waves with various wave ages of $c/u_* =$ 2, 14, and 25. Here, E_ω^x, E_ω^y, and E_ω^z are components of turbulent enstrophy in streamwise, transverse, and vertical directions, respectively; P_s^x is the production due to the stretching of vorticity fluctuations by the (phase averaged) strain; P_{st}^x is the production due to turbulent stretching; P_m^x is the mixed production.

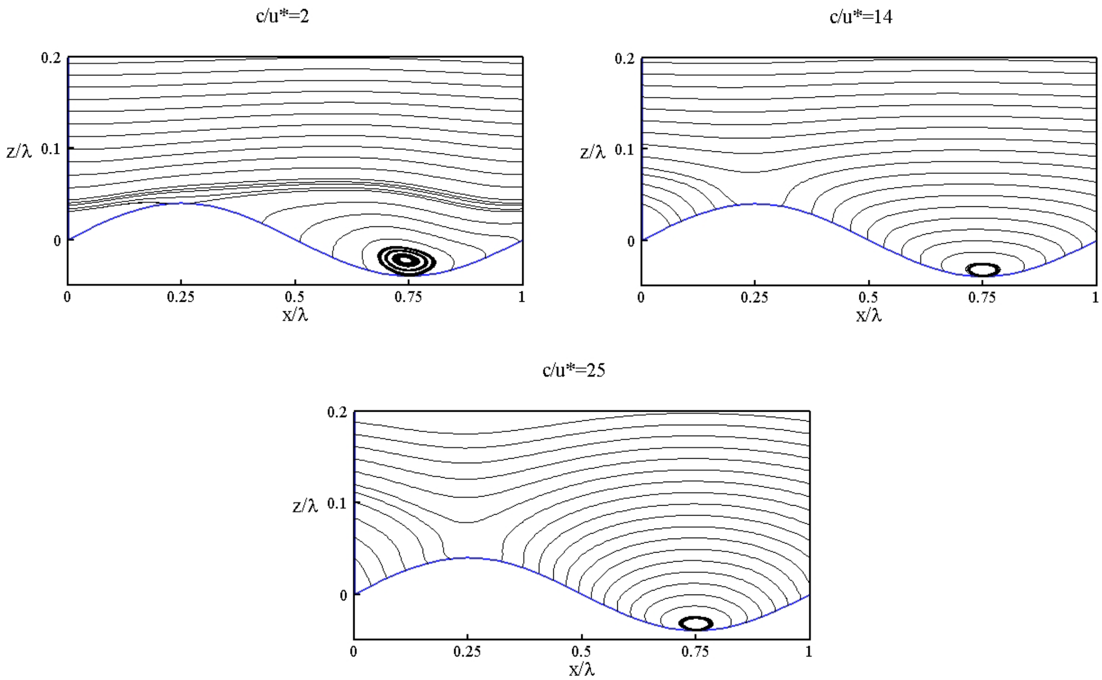

Figure 4. Phase-averaged streamlines of Eulerian velocity for winds over surface waves with various wave ages of $c/u_* =$ 2, 14, and 25.

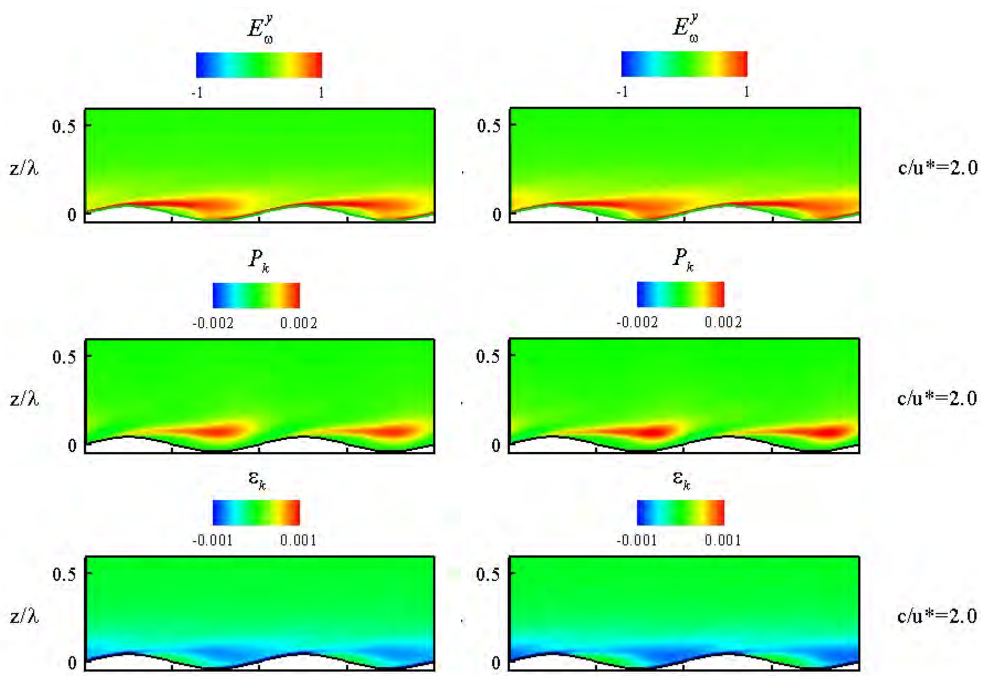

Figure 5. Effect of wind-induced surface drift on enstrophy and TKE budget. Here, the plots on the left are the cases without wind drift; on the right are the cases with wind drift.

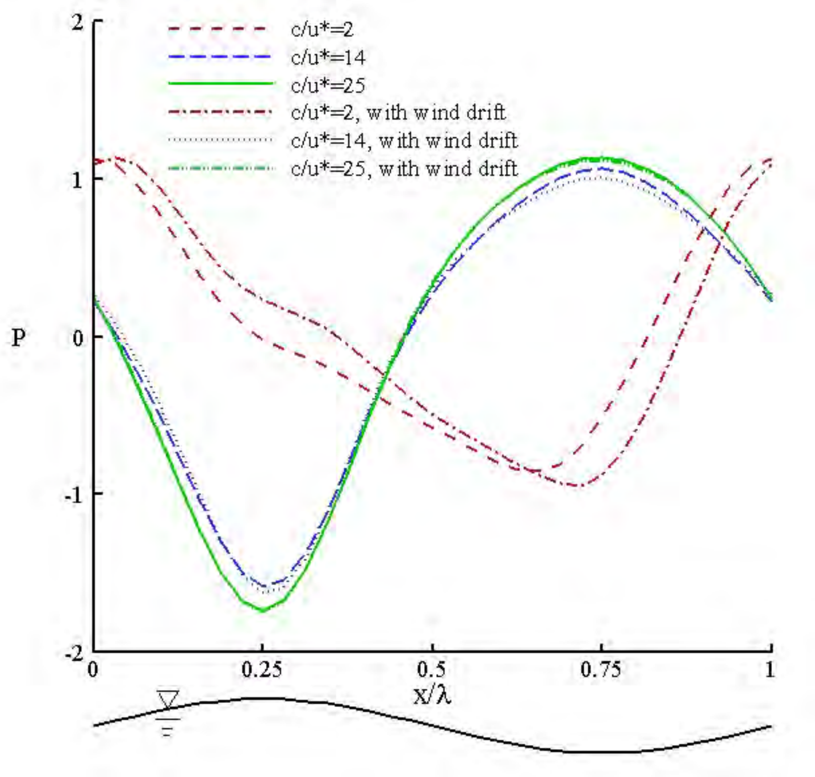

Figure 6. Phase-averaged pressure distribution along water wave surface. The solid line at the bottom illustrates surface elevation of the water wave. Here, the pressure is normalized by the root-mean-square value of the surface pressure fluctuation.